AIR PURIFICATION IN CLOSED ENVIRONMENTS: OVERVIEW OF SPACECRAFT SYSTEMS

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ABSTRACT

The primary goal for a collective protection system and a spacecraft environmental control and life support system (ECLSS) are strikingly similar. Essentially both function to provide the occupants of a building or vehicle with a safe, habitable environment. The collective protection system shields military and civilian personnel from short-term exposure to external threats presented by toxic agents and industrial chemicals while an ECLSS sustains astronauts for extended periods within the hostile environment of space. Both have air quality control design challenges in common with "tight" buildings.

Basic similarities between air purification system requirements for collective protection and an ECLSS that define surprisingly common technological challenges and solutions are summarized. Systems developed for air revitalization on board spacecraft are discussed along with a brief history of their early development as well as a view of future needs. Emphasis is placed upon two systems implemented by the National Aeronautics and Space Administration (NASA) onboard the *International Space Station* (*ISS*)—the trace contaminant control system (TCCS) and the molecular sieve-based carbon dioxide removal assembly (CDRA).

INTRODUCTION

Collective protection in the military and in support of civilian activities takes on many forms. Threats range from toxic warfare agents and toxic industrial chemicals (TICs) to biological agents. These are present in the external environment during an active threat and must be removed from makeup air supplied to a shelter to protect the occupants. Protection systems generally involve separation processes such as filtration and adsorption combined with other technologies as appropriate.[1] The scale of a collective protection system varies from that needed to protect a few soldiers to that for a large ship or building. Recent developmental emphasis for collective protection systems has been primarily on regenerable technologies.

Maintaining a habitable environment for astronauts in a spacecraft cabin is in many respects remarkably similar to military collective protection. Like a collective protection system, the main goal is to provide healthy, breathable air to humans. Table 1 provides a brief summary of the overlapping features of military collective protection and spacecraft environmental control and life support (ECLS) systems. Like spacecraft ECLS systems, collective protection systems share the need to minimize weight, power, and volume for some applications. Both employ overpressurization to protect the occupants from the external environment and very similar process technologies are employed. Unlike a collective protection system that is open by virtue of its use of an external makeup air supply, the closed environment in a spacecraft is an extreme example of the environment in a tight building.[2] The basic spacecraft cabin design philosophy for maintaining crew health has been shown to be applicable to tight building design.[3] As such, it has specific air revitalization needs to maintain the health of its occupants that are not ordinarily of much importance for military collective protection systems. These include trace chemical contaminant control, carbon dioxide partial pressure control, and humidity control. Chemical contaminants are present in spacecraft cabin air at trace concentrations as the result of equipment and materials offgassing as well as human metabolism. Human metabolism also contributes carbon dioxide and moisture to the cabin atmosphere. To maintain the crew's health and comfort, the carbon dioxide partial pressure and humidity must be maintained within acceptable levels.

To further explore the similarities between spacecraft ECLS systems and military collective protection systems, a brief history is provided that summarizes the NASA's development of spacecraft cabin air purification systems beginning with the short duration, single astronaut missions of Project *Mercury*. Emphasis is placed on two systems presently on board the *International Space Station* (*ISS*)—the trace contaminant control system (TCCS) and the carbon dioxide removal assembly (CDRA). Upon review of these systems, similarities and differences between spacecraft air purification systems and ground-based collective protection systems become evident. Future needs and directions are also considered. Similarities exist between air purification for a single astronaut on an extravehicular activity and single military or civilian personnel, but these are beyond the scope of this discussion.

Table 1. Collective protection vs. spacecraft life support systems.

PARAMETER	**JOINT SERVICES**	**NASA**
Design Needs	Many applications: minimum mass, volume, and power	All applications: minimum mass, volume, and power
Operation Time	Short (hours +)	Hours/days (*Mercury*) to months (*ISS*) or years (Mars exploration)
System Volume	Medium to very large (tank/fighter/shelter to ship)	Small (*Mercury*) to large (*ISS*)
Contaminant Source	External	Internal (equipment offgassing, crew metabolism, etc)
System Elements	Filtration Adsorption (single pass/PSA/TSA) Catalytic oxidation	Filtration Adsorption (single pass/VSA/TSA) Catalytic oxidation LiOH chemisorption Condensing heat exchange
Leaks	Yes, overpressurized	Yes, overpressurized but design is to achieve very small rates Some venting
Rehumidification	Typically of little concern	Yes
Speed	0 to Mach 2	Mach 25+

SPACECRAFT AIR PURIFICATION SYSTEMS

Background

Throughout the history of crewed space exploration, the NASA has developed and implemented a variety of spacecraft life support systems. As the duration and complexity of missions increased from minutes or hours for a single astronaut during Project *Mercury* to days and ultimately months for crews of 3 or more during the *Apollo*, *Skylab*, Shuttle, and *ISS* programs, these systems have become more sophisticated. Maintaining a safe, comfortable environment for the crew requires significant resources. Figure 1 summarizes the more than 30 kg of resources that must be supplied and the resulting byproducts that must be processed daily to support a single astronaut.[4] As mission duration and crew size have increased, Figure 1 makes it readily apparent that life support systems on board spacecraft such as the ISS must balance many competing factors. Primarily, their design must provide long-term environmental control and life support for a small mass, volume, and power penalty while maximizing their safety, reliability, and performance.

The balance between these competing design requirements becomes more difficult as exploration requires longer mission durations. To economically accommodate a longer mission and a larger crew, the need for a closed life support system, as shown by Figure 2, becomes paramount. As can be seen in Figure 2, there are distinct processes that comprise a spacecraft environmental control and life support system (ECLSS). These include systems for maintaining the temperature, humidity, carbon dioxide partial pressure, and trace contaminant concentrations in the cabin atmosphere. As well, systems that provide oxygen and process a variety of wastewater streams are required.

None of these systems operate alone. Interactions between cabin air quality and water processing system performance must be accommodated in the design. The key system interface for achieving a nearly closed ECLSS resides within the envelope containing the oxygen generation and carbon dioxide reduction processes. By combining the carbon dioxide removed from the cabin with residual hydrogen

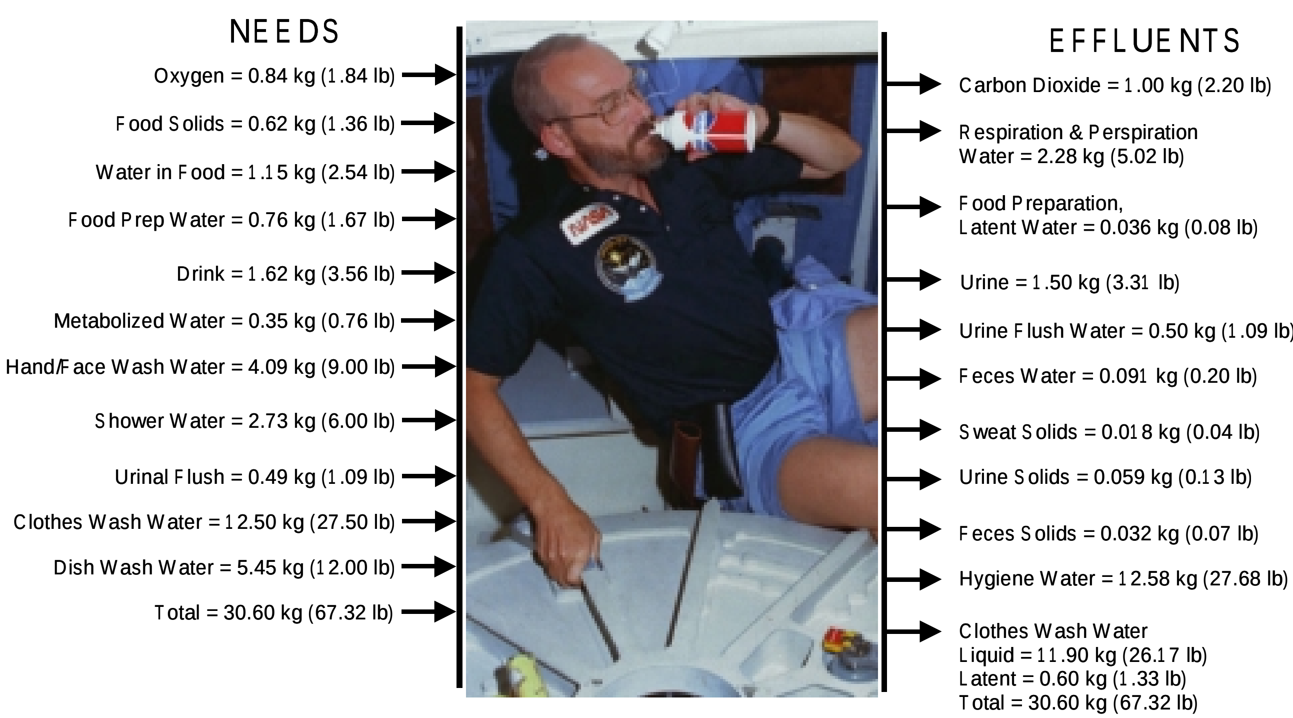

Figure 1. Crew needs and byproducts.

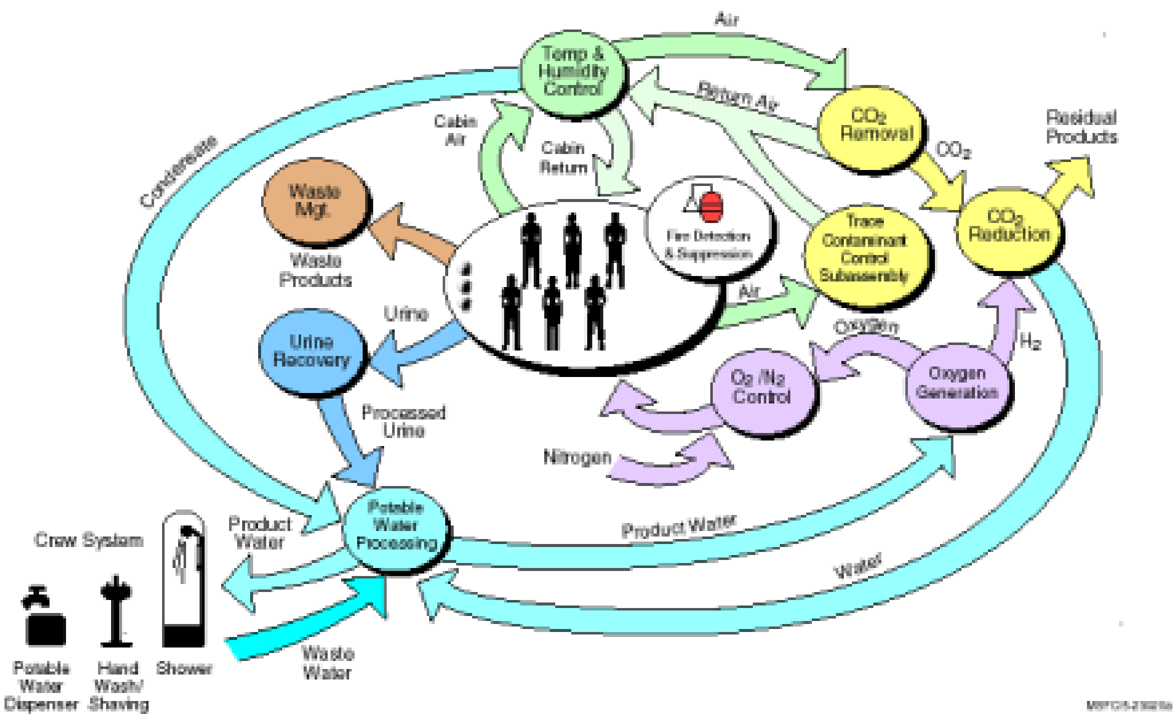

Figure 2. A closed environmental control and life support system.

from the oxygen generation process, additional water can be reclaimed. This scenario, of course, tends to drive the selection of some ECLSS technologies, particularly for the oxygen generation system. For instance, Figure 2 implies that water electrolysis is the system of choice for a closed ECLSS. Competing processes for processing wastewater streams and maintaining cabin air quality, however, are numerous.

Cabin Air Quality Maintenance

Maintaining acceptably clean spacecraft cabin air has been a concern from the beginning of crewed space exploration. Carbon dioxide partial pressure, trace chemical contaminant concentrations, and particulate matter concentration are the primary concerns beyond maintaining cabin temperature and humidity levels within healthy and comfortable limits. Table 2 summarizes the typical cabin air quality parameters for a crewed spacecraft while Figure 3 shows the basic interactions between factors that influence cabin air quality. Cabin air quality is the ultimate product of these interactions.[5]

Table 2. Spacecraft cabin air quality parameters.

PARAMETER	STANDARD
Carbon dioxide	5.3 mm Hg 24-hour average 7.6 mm Hg maximum
Oxygen	19.5-23 kPa
Water vapor	4.4-15.5°C dewpoint
Trace chemical contaminants	Less than 180-day SMAC*
Particulate matter	0.2 mg/m^3 for 0.5-100 micron
Microbes	500 CFU bacteria/m^3 100 CFU fungi/m^3

*Spacecraft maximum allowable concentration.

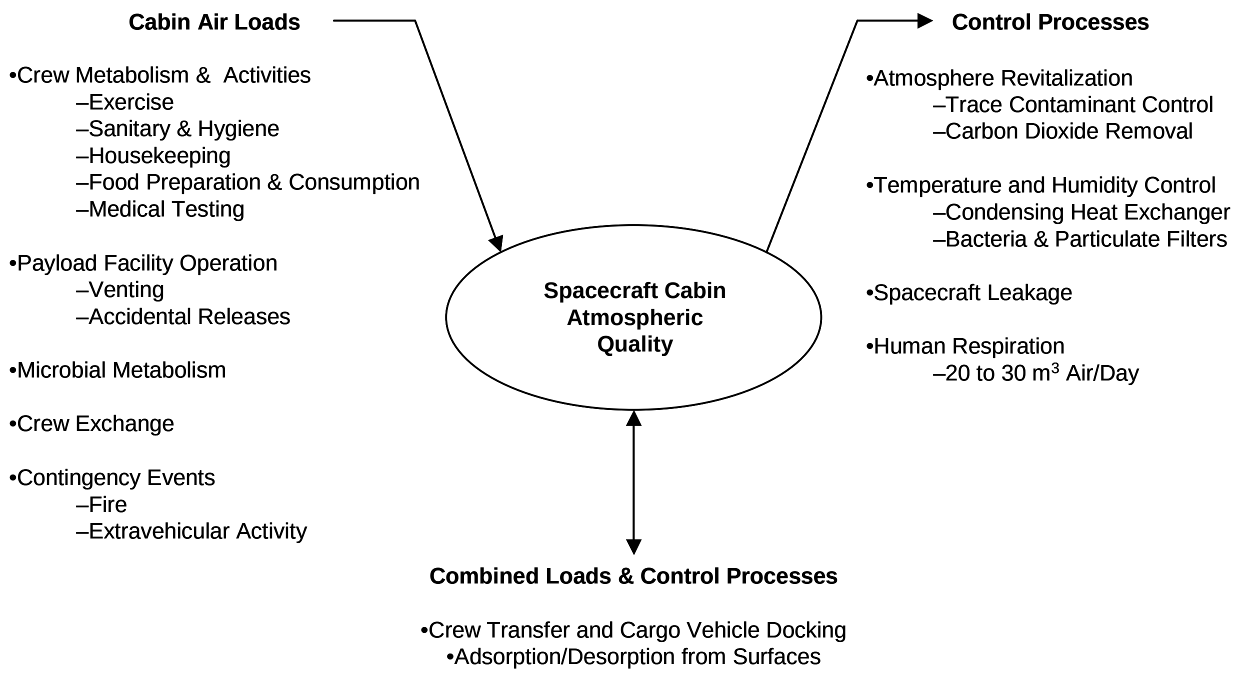

Figure 3. Factors influencing spacecraft cabin air quality.

History of Air Quality Control Systems

Table 3 provides a summary of the air purification technologies used on NASA spacecraft. The early programs, *Mercury*, *Gemini*, and *Apollo*, employed equipment that relied heavily upon physical and chemical adsorption and course particulate matter filtration to address these challenges. *Skylab*, America's first space station, employed a similar approach for cabin air purification with the exception that carbon dioxide partial pressure control was provided by a pressure swing adsorption system. Trace chemical contamination control still relied upon expendable adsorption beds. Likewise, screens provided course particulate matter filtration. Little change was realized with the development of the Space Shuttle. Air purification systems used on board the Shuttle Orbiter actually reverted to systems similar to those used before *Skylab*. Expendable chemical and physical adsorption systems have been the rule. As a result, mission duration is limited to 15 days or less. For 3 missions, a pressure swing chemisorption process based upon solid amines was demonstrated for carbon dioxide partial pressure control.[6] However, this system had to use expendable resources to address requirements for redundancy. Recent work has been undertaken to address the redundancy issues.[7, 8] However, this new system is in the conceptual design stages. Overall, broad application of regenerable processes for cabin air quality control was not realized until the development of the *ISS*.[9, 10]

International Space Station Cabin Air Purification

Cabin air quality control systems on board the *ISS* employ chemical adsorption, physical adsorption, and thermal catalytic oxidation processes to maintain acceptable cabin air quality. Their primary function is to remove carbon dioxide and trace chemical contaminants from the cabin air. The processes that provide this function are part of the atmosphere revitalization subsystem (ARS). Within the ARS, the air is processed in parallel by two unit operation strings. The first is the carbon dioxide removal assembly (CDRA) and the second is the trace contaminant control subassembly (TCCS). Both the systems are housed in a standard *ISS* equipment rack, shown by Figure 4, located in the U.S. On-orbit Segment (USOS) Laboratory Module.

Table 3. Summary of spacecraft cabin air purification technologies.

PROJECT	MISSION DURATION	CABIN VOLUME (m^3)	CREW SIZE	AIR QUALITY TECHNOLOGIES
Mercury	34 hours	1.56	1	CO_2 removal: LiOH Trace contaminants: activated carbon
Gemini	14 days	2.26	2	CO_2 removal: LiOH Trace contaminants: activated carbon
Apollo	14 days	5.9	3	CO_2 removal: LiOH Trace contaminants: activated carbon
Skylab	84 days	361	3	CO_2 removal: Type 13X and 5A molecular sieves regenerated by pressure swing Trace contaminants: activated carbon
Shuttle	14 days	74	7	CO_2 removal: LiOH Trace contaminants: activated carbon with ambient temperature CO catalytic oxidation
Space Station	180 days	Up to 600	3 to 6	CO_2 removal: Silica gel with type 13X and 5A molecular sieves regenerated by combined pressure/thermal swing Trace contaminants: activated carbon with thermal catalytic oxidation

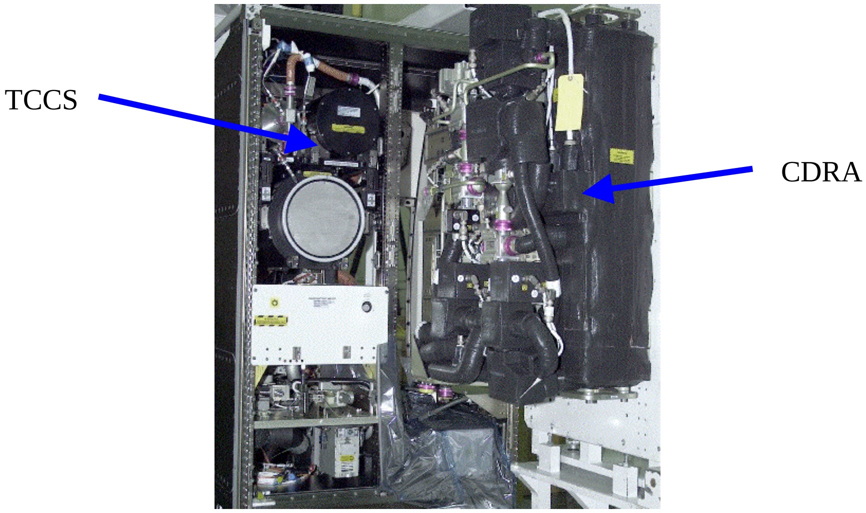

Figure 4. USOS atmosphere revitalization subsystem rack.

Carbon Dioxide Removal Assembly

The CDRA, shown schematically by Figure 5, maintains the cabin's carbon dioxide partial pressure within the allowable range of Table 2 to maintain crew health. Its primary components include 4 adsorbent beds, a blower, an air save pump, and 6 selector valves. As shown by Figure 5, cabin air enters the CDRA in the range of 19.5–40.8 kg/h. The inlet air has first been cooled to its dewpoint before entering the CDRA. This reduces the total water load on the system. The inlet air flows through the adsorbing desiccant bed to remove additional water. This bed contains zeolite 13X and silica gel in alternating layers. Zeolite 13X occupies the first 290 cm^3 of the bed volume. This layer of zeolite protects the silica gel, which occupies the next 6,600 cm^3 of the bed, from entrained water droplets. Entrained liquid water can cause the silica gel to swell and fracture. The remaining 5,900 cm^3 of the bed is packed with more zeolite 13X. The process air exiting the desiccant bed typically has a dewpoint ranging from –62 to –73 °C. Upon exiting the desiccant bed, the air enters the adsorbing carbon dioxide adsorbent bed. This bed has a packed volume of 16,000 cm^3 containing zeolite 5A. The air exits through the desorbing desiccant bed. Exhaust air is directed back to the humidity control system to recover the moisture as condensate. The CDRA's normal regeneration cycle takes approximately 144 minutes. During regeneration, the carbon dioxide adsorbent bed is evacuated by a pump, heated to 204 °C, and exposed to space vacuum. The initial evacuation is designed to minimize atmospheric gas losses overboard. Heating the bed requires nearly 1 kW of power. [11, 12]

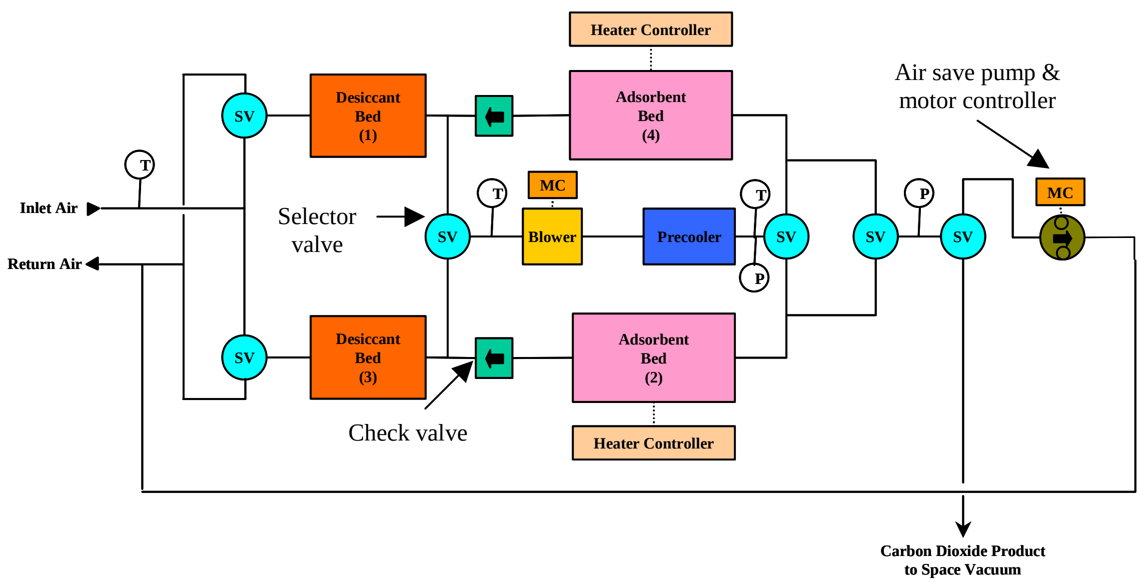

Figure 5. Simplified carbon dioxide removal assembly process diagram.

Trace Contaminant Control Subassembly

Three main components comprise the TCCS. They are an expendable activated carbon bed, a thermal catalytic oxidizer, and an expendable post-sorbent bed. Additionally, the TCCS contains a blower, flow meter, and electrical interface assembly. The TCCS has a long development history dating to the late 1960s. Its primary design was first built and tested in the mid-1970s and has changed little since. In the *ISS* application, process air enters the TCCS directly from the cabin. Unlike the CDRA, the inlet air is not processed to remove moisture. The process flow rate is 15.3 m^3/h through the carbon bed, which contains 22.7 kg of granular activated carbon treated with 10% by weight phosphoric acid. The phosphoric acid treatment prevents ammonia from entering the thermal catalytic oxidizer. Upon exiting the carbon bed, the process stream splits. Approximately one-third of the air flows through the thermal catalytic oxidizer and post-sorbent bed before rejoining the bypass stream just before the system exhaust. Principle parts of the thermal catalytic oxidizer include a recuperative heat exchanger, an electric heater, and a catalyst bed. The catalyst bed contains approximately 1 kg of platinum group metal catalyst supported on alumina pellets. The heater requires approximately 167 Watts of power at 100% duty and an average of 120 Watts of power under normal operation. After passing through the catalytic oxidizer, the process stream passes through a bed of lithium hydroxide to remove any acidic oxidation products. Typical expendable bed service life is 1 year for the carbon bed and 2.5 years for the post-sorbent bed.[13]

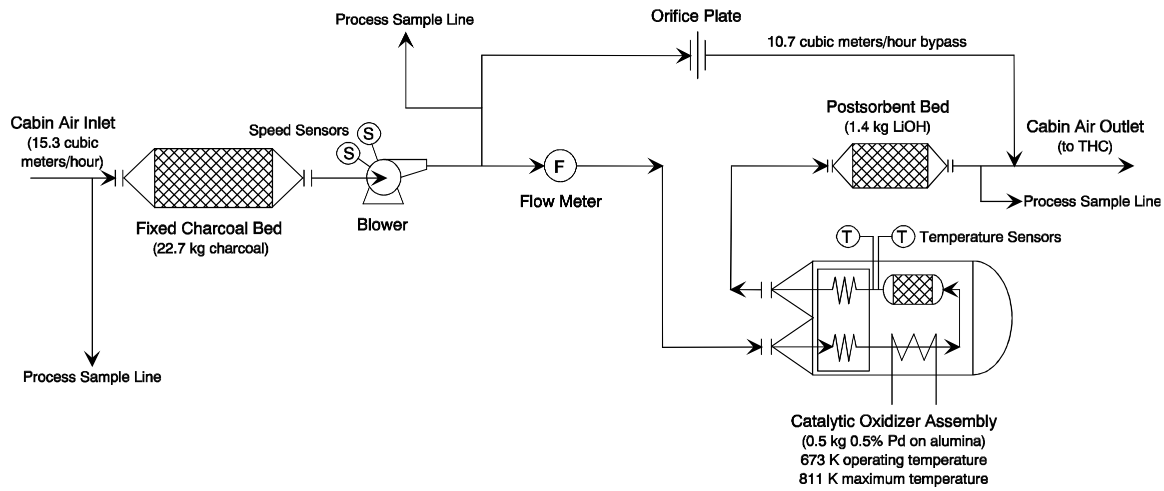

Figure 6. Simplified trace contaminant control subassembly process diagram.

Future Spacecraft Air Quality Control Technologies

As crewed space exploration mission durations increase and objectives push beyond low Earth orbit, improvements are needed to further minimize air purification system mass, power, volume, and logistics requirements. Experience has demonstrated that air purification technologies based upon adsorption and catalytic oxidation work well; however, process inefficiencies and the continued reliance upon expendable resources present challenges to extending the boundaries of space exploration. Efforts to attack thse inefficiencies for the *ISS* and beyond have been defined and development efforts are making progress.[14]

Advances in regenerable adsorbent media and oxidation processes are under development for the next generation of spacecraft air quality control systems. Not only must this next generation of air purification processes provide broad spectrum air quality control in a small volume, low power package, but it must also provide up to a factor of 3 reduction in logistics mass. To this end, the NASA sponsors advanced ECLS technology development that attacks various process inefficiencies. Some of the more promising technologies for space applications are the following:

1. Solid amine chemical adsorbent media for carbon dioxide control.[7, 8]
2. Structured oxidation catalyst substrates that improve mass transfer, allow direct catalyst heating, and compact reactor design.[15, 16, 17, 18]
3. Structured adsorbent substrates to eliminate adsorbent bed dust generation caused by size attrition and reduce volume, mass, and power required for temperature swing adsorption systems.[19]
4. Adsorbents for use in combined temperature-pressure swing trace contaminant control system to reduce logistics requirements and improve process safety.[20, 21]

SIMILARITIES AND DIFFERENCES WITH COLLECTIVE PROTECTION

Several similarities between ECLS and collective protection systems beyond those summarized by Table 1 are notable. These include the need to remove chemical contaminants from the air and to operate reliably while consuming few resources. As well, there are significant similarities with respect to the technologies employed by the systems. Some of the most striking similarities and notable differences are presented by the following brief discussion.

First, for both the NASA and the military, a broad spectrum of chemical contaminants is of concern. While the trace chemical contaminant load presented to the ECLS system by equipment offgassing and crew metabolism is low by collective protection system standards, both must deal with a variety of common TICs. The size of the challenge, however, can be quite different with the ECLS system challenge at trace levels compared to that experienced by a collective protection system. In addition, the collective protective protection system must defeat very specific threats from choking, nerve, blood, and blister agents.

Both ECLS and collective protection systems stress minimal reliance on consumables, minimum size, low power, and high reliability. Technological solutions such as filtration and adsorption in combination with others such as catalytic oxidation are common ingredients to addressing challenges facing spacecraft ECLS and collective protection systems. Future trends are toward fully regenerable technologies. Of course, there are differences between the NASA's and the military's needs and designs.

The NASA has greater concern for controlling carbon dioxide removal and humidity levels in addition to dealing with chemical and biological contamination. Also, in general, a spacecraft's ECLS system is challenged by low concentrations continuously and for long periods of time whereas the threats that must be met by a collective protection system are transient.

CONCLUSION

The air purification systems deployed on board various spacecraft ranging from single astronaut applications like Project *Mercury* through the crew needs of the *ISS* and beyond have been briefly reviewed. These spacecraft systems have several remarkable similarities with military collective protection systems. Notably, both share the common goal to provide a habitable environment for humans by protecting them from a hostile external environment. Because there are overlaps of the design challenges facing collective protection system and spacecraft ECLSS developers, the technological solutions being pursued are quite similar. By recognizing these similarities, future collective protection and spacecraft ECLSS development may benefit significantly through collaborative efforts.

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